Ultraluminous x-ray sources, high redshift QSOs and active galaxies

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ABSTRACT

It is shown that all of the 32 point X-ray sources which lie within about 10' of the centre of nearby galaxies, and which have so far been optically identified, are high redshift objects – AGN or QSOs. Thus the surface density of these QSOs $\rho \simeq 0.1$ per square arc minute. Some of them were originally discovered as X-ray sources and classified as ultraluminous X-ray sources (ULXs), nearly all of which lie near the centers of active galaxies. We demonstrate that this concentration around galactic nuclei is of high statistical significance: the probability p that they are accidental lies in the range $10^{-3} - 10^{-4}$, and apparently this excess cannot be accounted for by microlensing.

Subject headings: QSOs - galaxies

1. Introduction and data

Optical identifications of compact X-ray sources have shown that they may be (a) binary star systems where accretion of matter from the optically luminous star on to a companion neutron star or black hole is the primary energy source, (b) quasi-stellar objects with a wide range of redshifts, or (c) the nuclei of active galaxies. High resolution studies made with Einstein, Rosat, Chandra and XMM have shown that powerful point X-ray sources displaced from the nuclei of the galaxies can be found apparently very close to or in the main bodies of many comparatively nearby galaxies (cf Colbert et al, 2002; Fabbiano et al, 2001; Foschini et al, 2002a&b; Kaaret, Makishima, et al, 2000; Strickland et al, 2001; Wu et al 2002; Zezas et al, 2002). The distances of all these galaxies are so large that the luminosities of these X-ray sources must be $\simeq 10^{39} \ erg \ s^{-1}$. Thus if they are binaries similar to those identified in our

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own galaxy they may be black hole accretion sources with masses in the range 10^3 – $10^4 \,\mathrm{M}_{\odot}$, or possibly accretion sources with lower masses but which are beamed. While there have been many x-ray studies of these sources, very few have been optically identified.

In 2003, we suggested that some of them might, instead, be X-ray emitting QSOs with a wide range of redshifts (Burbidge et al 2003). In that case they might have been identified first as QSOs very close to the nuclei of galaxies, and then found later to be X-ray sources. Alternatively, from the X-ray detections of ULX sources, accurate enough positions might enable us to identify optical objects which turn out to be QSOs.

It turns out that both methods have worked. We have surveyed the literature and show in Table 1 a list of all the known X-ray emitting QSOs which lie within $\sim 10'$ of the centers of comparatively nearby galaxies. From the redshifts of these galaxies and using a Hubble constant of 60 km s⁻¹ Mpc⁻¹ (Tamman et al 2002), it can be seen that all of the galaxies lie within about 35 Mpc. Nearly all of them show signs of activity in their nuclei.

All types of galaxies have been surveyed for ULXs and there is some indication that more ULX's are found in elliptical galaxies than in spirals (cf Colbert & Ptak 2002). Thus it may well be that a significant number of the ULXs are black hole accretion binaries since there is no evidence for nuclear activity in most of those galaxies. So, as far as we are aware there are, as yet, no optical identifications of any ULXs which are binary systems. However the brightest ULX in M82 has been shown from X-ray observations to show variations giving an orbital period of about 62 days (Kaaret, Simet and Lang 2006). Of course this is not an optical identification but it does suggest that this is a binary source, and we do not doubt that many ULXs still to be identified are massive binaries.

However, the main point of this paper remains. Table 1 demonstrates that many ULX sources are high redshift QSOs as we suggested in 2003 (Burbidge et al 2003)

2. Concentrations of ULX QSOs around nearby galaxies

There have been numerous claims in the literature that QSOs tend to concentrate around nearby, active galaxies (cf Radecke and Arp, 1997). Since only ULX QSOs within 10 arc minutes of a galactic nucleus were selected in the present study, the hypothesis that they are significantly concentrated around galaxies should be tested by comparison with other samples of X-ray emitting QSOs. An ideal 'null sample' would be the general background of ULX QSOs. Instead, comparison is here made with the background density of QSOs in general since this appears to be well-known as a function of magnitude (Kilkenny et 1997; Myers et al. 2005). Since only a fraction of background QSOs are X-ray sources, the statistical

significance of any concentration will thereby be underestimated.

In Fig. 1 the magnitude distribution of the Table 1 ULX QSOs is compared with that derived from the Sloan Digital Sky Survey (Myers et al. 2005). It is clear that the sample contains a disproportionately large number of very bright QSOs. A t-test reveals the excess to be significant at a confidence level $\sim 10^4$ to one. The median magnitude from Table 1 is 19.3, although absorption by the intervening galaxies may imply that some or all are intrinsically brighter. The total number of galaxies which have been surveyed using X-ray telescopes to find ULXs is about 200. However, very little work has been done on optical identifications in general, and all of the positively identified ULXs are those in Table 1. If we conservatively assume that 20 galaxies have been surveyed in arriving at these identifications, then the area of sky searched for Table 1 is about 1.75 square degrees. Observer bias could have entered through selective surveying of ultraluminous sources close to galactic nuclei. Thus in NGC 720, four QSOs have been identified within 4' of the nucleus but none are listed between 4' and 10'. Does this reflect a real concentration in the sky, or a choice of targets by the observer? The question can be circumvented by testing any apparent concentration against the total background count expected for any prescribed limiting magnitude, obtained from homogeneous QSO surveys.

There is clearly a significant surfeit of very bright QSOs and of QSOs very close to the galactic nuclei. The former result is illustrated in Fig. 2 for QSOs with b < 17.5, which reveals an excess of such objects at all angular distances out to 10'. There are two such objects within 3' as against an expectation of 0.027 (probablility $p \sim 3.6 \times 10^{-4}$) increasing to 4 within 10' as against an expectation of 0.297 ($p \sim 2.6 \times 10^{-4}$). Also, there are five QSOs brighter than 19.0 within 3' of the nuclei as against an expectation of 0.67, a result which has $p \sim 6.2 \times 10^{-4}$. These probabilities are likely to be conservative in that:

- (i) they are derived assuming 100% discovery of bright ULX QSOs out to 10';
- (ii) comparison is made with the total QSO background density rather than the background of ultraluminous QSOs; and
- (iii) in the null hypothesis no correction for dimming of the QSOs is made although on the conventional interpretation they are seen through the galaxies ($\lesssim 100 \text{ kpc}$).

The referee has made the point that we have assumed here that only about 20 out of $\simeq 200$ spiral galaxies are know to contain ULX sources which are high redshift QSOs. He is correct in pointing out that if all 200 had been studied, the total area used in our calculation would be 17.5 square degrees. Thus if no more QSOs were found in the remaining galaxies the probabilities that these concentrations are accidental would be increased by factors of 10. However, we strongly suspect that many more QSOs will be found in the galaxies still to be surveyed. But, very conservatively we can conclude that the density ρ of bright QSOs

in the nuclear regions of galaxies lies somewhere in the range $0.1 > \rho > 0.01$ per square arc minutes.

3. Discussion and Conclusion

Assuming the halo of each galaxy to have a mass $10^{12} \,\mathrm{M}_{\odot}$ in the form of microlenses, then the 14 galaxies have an aggregate microlensing area equivalent to a single object of Einstein radius $\Theta_E \sim 85$ arcsec, corresponding to an area ~ 0.024 sq deg or about 2 percent of the area under consideration.

To boost the expected number of bright QSOs (say <17.5 mag, with background density ~ 0.15 per square degree) from the expectation value ~ 0.3 to the observed 4 would require the lensing of faint QSOs within the Einstein radii with background densities at least two orders of magnitude higher, i.e. magnitude 20.5 or fainter. Microlensing both enhances the brightness of faint background QSOs and lowers their density over the sky. Because of the shallowness of the slope at the faint end of the QSO distribution – below the knee at $b_0 = 19.1$ – microlensing creates a deficit rather than an excess of counts (Myers et al. 2005).

Myers et al (2005) have remarked that standard Λ CDM models have difficulty producing the QSO excess they find on 100 kpc scales, and remark that either bias is strongly scale dependent, or "there exists an unexpected, strong systematic effect inducing positive correlations between QSOs and foreground galaxies". The above argument suggests that even with halo masses $\sim 10^{12}\,\mathrm{M}_{\odot}$, microlensing is unable to account for the observed excess. This would seem to support the view that at least a proportion of the ULX QSOs are physically close to the nuclei of galaxies. Clearly some of ULX sources are high redshift QSOs closely associated with the galaxies.

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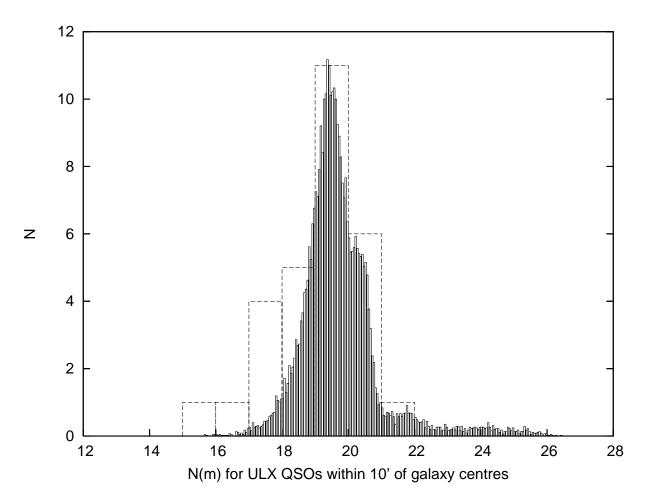


Fig. 1.— Magnitude distribution of ULX QSOs in Table 1 (histogram) as compared with that from the Sloan Survey, suitably normalised (solid curve).

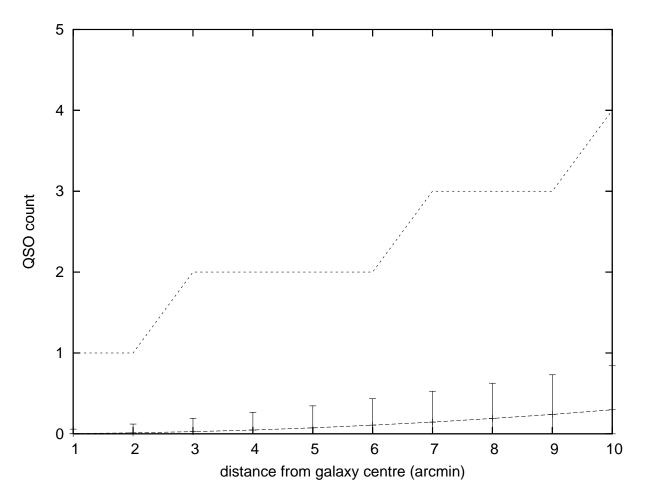


Fig. 2.— Upper curve: cumulative numbers of ULX QSOs with b <17.5 as a function of angular distance from the galaxy nuclei. Lower curve: expected background count for all QSOs, whether ULX or not, assuming 100% completeness of discovery. Error bars are 1σ limits based on Poissonian estimates.

Table 1: X-Ray Emitting QSOs Lying Within 10' of Galaxy Centers

Table 1: A-Ray Emitting Q5Os Lying Within 10 of Garaxy Centers							
GALAXY	TYPE	z_G	z_Q	m_Q	Θ	d (kpc)	SOURCE
NGC 720	E4	0.0058	0.39	21.5	1.9	15.8	Burbidge et al (2005b)
			0.39	22.0	2.3	19.6	
			0.96	19.2	2.7	27.9	Arp et al (2004)
			2.22	20.6	3.4	35.1	
NGC 1073	SB(rs)c	0.0040	1.41	20.0	1.4	12.3	Arp & Sulentic (1979)
			0.56	18.8	2.1	18.4	Burbidge et al (1979)
NGC 1365	(R')SBb(c)b	0.0055	0.90	19.7	7.7	95.9	LaFranca et al (2002)
	Sy1.8		0.31	18.0	12.4	154.5	
NGC 3079	SB(S)c	0.0037	1.04	19.1	8.8	94.7	Arp et al (2005)
	Sy2		0.680	21.0	7.5	80.7	Burbidge et al (2005a)
			0.673	18.5	10.0	107.6	
			0.216	17.5	13.0	140.0	
NGC 3628	Sab pec	0.0028	0.995	20.1	3.0	18.3	Arp et al (2002)
	Liner		2.150	19.5	4.2	25.7	
			0.981	19.2	5.5	33.6	
			0.408	19.6	5.6	34.2	
			2.430	19.9	6.0	36.7	
			2.060	19.6	7.9	48.3	
			1.940	18.3	12.3	75.2	
NGC 4039	SA(S')m Liner	0.0055	0.26		0.34	3.4	Clark et al (2005)
NGC 4151	(2')SAB(rs)	0.0033	0.613	20.3	4.9	36.8	Page et al (2001)
	Sy 1.5		0.022	17.2	6.8	56.1	Rector et al (2000)
NGC 4168	E2 Sy 1.9	0.0074	0.217	18.7	0.75	4.8	Masetti et al (2003)
NGC 4203	SABO Liner	0.0036	0.614	17.5	2.1	13.1	Knezk & Bregman (1998)
NGC 4258	SAB(s)bc	0.0015	0.398	20.4	8.6	39.6	Burbidge (1995)
	Sy 1.9		0.653	19.9	9.7	44.7	Mironi (2003)
			0.520	17.0	9.7	44.7	
NGC 4319	SB(r)ab AGN	0.0045	0.071	15.2	0.7	4.6	Stocke et al (1991)
NGC 4374	E1 Sy2	0.0035	1.25	18.5	2.4	15.3	Burbidge et al (1990)
NGC 4698	SA(S)ab Sy2	0.0033	0.43	20.5	1.2	5.7	Foschini et al (2002)
NGC 7319	SB(s)bc Sy2	0.0023	2.11	21.8	0.13	4.3	Galianni et al (2005)